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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of:

Applicants: Oskar PAINTER, Ming CAI, Kerry VAHALA and Peter C. SERCEL

Serial No: Not yet assigned

Filed: 09 March 2001

For: **MICRO-CAVITY LASER**

BOX PATENT APPLICATION
Assistant Commissioner for Patents
Washington, D.C. 20231

Dear Sir:

Transmitted herewith for filing is the non-provisional patent application identified above.

- ☒ 9 sheets of drawings (☐ formal ☒ informal) are enclosed.
- ☒ 32 pages of specification and 1 page of abstract of the invention are enclosed.
- ☒ An un-executed assignment of the invention to CALIFORNIA INSTITUTE OF TECHNOLOGY and ALEPH LIGHTGATE CORPORATION is enclosed.
- ☐ An associate power of attorney ☐ is enclosed ☐ will follow.
- ☒ An un-executed verified statement to establish small entity status under 37 C.F.R. §§ 1.9 & 1.27 for CALIFORNIA INSTITUTE OF TECHNOLOGY is enclosed.
- ☒ An un-executed verified statement to establish small entity status under 37 C.F.R. §§ 1.9 & 1.27 for ALEPH LIGHTGATE CORPORATION is enclosed.
- ☒ An un-executed Declaration and Power of Attorney is enclosed.
- ☒ Priority is claimed on U.S. Provisional Patent Application Serial No. 60/188325 filed on 09 March 2000.

CALCULATION OF FEES								
	ITEM	TOTAL NO. OF CLAIMS		NO. OF CLAIMS OVER BASE	LG/SM $ ENTITY FEE		$ AMOUNT	$ FEE
A	TOTAL CLAIMS FEE	59	-20	39	LG=$18 SM=$9	351.00	351.00	N/A
B	INDEPENDENT CLAIMS FEE*	8	-3	5	LG=$78 SM=$39	195.00	195.00	N/A
C	SUBTOTAL - ADDITIONAL CLAIMS FEE (ADD FINAL COLUMN IN LINES A+B)							546.00
D	MULTIPLE-DEPENDENT CLAIMS FEE					LARGE ENTITY FEE=$260 SMALL ENTITY FEE=$130		
E	BASIC FEE					LARGE ENTITY FEE=$760 SMALL ENTITY FEE=$380		380.00
F	TOTAL FILING FEE (ADD TOTALS FOR LINES C, D, AND E)							926.00
	*LIST INDEPENDENT CLAIMS [LIST OF INDEPENDENT CLAIMS]							N/A

☒ A check in the amount of $926.00 over the filing fee is enclosed.

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- ☐ Any additional filing fees required under 37 C.F.R. § 1.16
- ☐ Any patent application processing fees under 37 C.F.R. § 1.17

Respectfully submitted,

Date: 09 March 2001

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CERTIFICATION UNDER 37 CFR 1.10

I hereby certify that this paper and the documents referred to as enclosed therein are being deposited with the United States Postal Services on this date **09 March 2001** in an envelope as "Express Mail Post Office to Addressee" Mailing Label Number **EL631470561US** addressed to the "**BOX NEW PATENT APP/FEE, Assistant Commissioner for Patents, Washington, D.C. 20231**".

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Print name of person mailing documents

APPLICATION FOR UNITED STATES PATENT

IN THE NAME OF

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ASSIGNED TO

California Institute of Technology
and
Aleph Lightgate Corporation

for

MICRO-CAVITY LASER

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SPECIFICATION

This application claims priority on United States provisional application No. 60/188,325, filed March 9, 2000, and entitled, "Fiber-Coupled Microsphere Laser." The disclosure of the foregoing is incorporated by reference herein as if set forth in full hereat.

FIELD OF INVENTION

The field of the invention relates to lasers and certain related methods, and in particular to micro-cavity lasers and related methods.

BACKGROUND OF THE INVENTION

In the now rapidly expanding technology relating to the use of optical waveguides and in particular fiber optic waveguides, a number of discrete devices and subsystems have been developed to modulate, route or otherwise control, optical beams that are at specific wavelengths. Present day communication systems increasingly use individual waveguides to carry densely wavelength multiplexed optical beams. Thus, there is a need for a self-contained device and related methods which can induce a lased output in a frequency range of interest. Currently, the telecommunications industry uses frequencies in the 1550 nm range.

It is known to one of ordinary skill in the art how to couple a waveguide to an optical resonator so as to transfer optical power to the resonator from the waveguide or from the waveguide

to the resonator. It is also known to one of ordinary skill in the art that power circulates in a resonator preferentially at resonant frequencies corresponding to optical modes of the resonator. For the purposes of discussion the terms resonance and optical mode will be used interchangeably herein. Likewise the principles associated with lasing action in resonators and in particular rare earth doped resonators and micro-resonators are well understood to one of ordinary skill in the art. The terms micro-cavity, resonator, micro-resonator will be used interchangeably herein. Discussion of these concepts can be found in one or more of the following references, the disclosure of each of which is incorporated by reference herein as if set forth in full hereat: V. Lefevre-Seguin and S. Haroche, Mater. Sci. Eng. B**48,** 53 (1997); J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, Opt. Lett. **22,** 1129 (1997); M. Cai, O. Painter, and K. Vahala, Phys. Rev. Lett. **85,**74 (2000); M. Cai and K. Vahala, Opt. Lett. **25,** 260 (2000); V. Sandoghdar, F. Treussart, J. Hare, V. Lefevre-Seguin, J. M. Raimond, and S. Haroche, Phys. Rev. A **54,** 1777 (1996); W. von Klitzing, E. Jahier, R. Long, F. Lissillour, V. Lefevre-Serguin, J. Hare, J. M. Raimond, and S. Haroche, Electron. Lett. **35,** 1745 (1999); P. Laporta, S. Taccheo, S. Longhi, O. Svelto, and C. Svelto, Opt. Mater. **11,** 269 (1999); V. B. Braginsky, M. L. Gorodetsky, and V. S. Ilchenko, Phys. Lett. A **137,** 393 (1989); A. Serpenguzel, S. Arnold, and G. Griffel, Opt. Lett.**20,** 654 (1995); V. S. Ilchenko, X. S. Yao, and L. Maleki, Opt. Lett. **24,**723 (1999); M. L. Gorodetsky and V. S. Ilchenko, J. Opt. Soc. Am.B **16,** 147 (1999); T. Baer, Opt. Lett. **12,** 392 (1987); G. H. B. Thompson, *Physics of Semiconductor Laser Devices* (Wiley, New York, 1980); T. Mukaiyama, K. Takeda, H. Miyazaki, Y. Jimba, and M. Kuwata-Gonokami, Phys. Rev. Lett. **82,** 4623 (1999);

The theoretical concept of inducing lasing action in a micro-resonator doped with Nd is discussed by F. Treussart, et al., in Eur. Phys. J. D **1**, 235 (1998), the disclosure of which is incorporated by reference herein as if set forth in full hereat. This reference, however, presents a device which relies on the use of prisms to couple to the laser resonator. Such a configuration presents many difficulties and limitations on its use in the field, as it requires delicate and precise alignment, is bulky and not easily adaptable common use and does not produce an output frequency which is currently of most use in the telecommuting industry. Additional limitations of these and other devices include low emission and coupling efficiencies.

The present invention overcomes these and the other limitations of the prior art by providing a compact, self-containable laser source that is directly coupled to an optical fiber waveguide. Optical fibers, in addition to being very important in modern optical communications systems, provide a very convenient means to convey both optical pump power to the laser as well to convey emitted laser radiation from the laser resonator. The ability to directly couple laser emission to an optical fiber is therefore of great practical significance. The output frequency of the present invention can be tuned both by design (based on choice of certain materials and/or dopants utilized) and dynamically (by varying the frequency of the laser pump signal) and by incorporation of grating structures into the micro-cavity. The present invention also provides a laser source with improved emissions and increased coupling efficiency between the waveguide and the resonator. Finally, the each of the preferred embodiments can be made to be robust and easy to implement in a variety of configurations and uses.

SUMMARY OF THE INVENTION

The present invention is directed to a micro-cavity laser and certain related methods. The devices and methods of the present invention are useful for creating laser signals having a frequency within a desired range by optically coupling an optical pump signal in a waveguide to a micro-cavity optical resonator, which resonator includes an active medium which is capable of providing optical gain upon pump excitation and which resonator and pumped active medium result in lasing action at a frequency within the desired output range. In the preferred embodiments, the waveguide is a fiber waveguide of any configuration and the coupling between the fiber waveguide and the resonator is by means of an optical couple between a fiber taper in the fiber waveguide and the micro-cavity optical resonator. In the preferred embodiment the fiber waveguide serves to both transport optical pump power to the resonator to excite the amplifying medium as well as to collect lasing emission from the laser cavity and transport it to elsewhere. The fiber waveguide and the resonator are preferably critically coupled at the pump wavelength so as to maximize pump power coupling to the active medium. In addition, it is possible and important to phase match the fiber taper and the micro-cavity resonator so as to maximize the coupling efficiency between these two elements of the present invention.

In another embodiment two fiber waveguides are coupled to the micro-cavity and each is optimized for coupling of pump power or collection of laser emission. In this embodiment phase matching could be employed to perform this optimization.

The micro-cavity optical resonator can have a variety of shapes including, without limitation, a microsphere, one or more micro-rings, racetracks or disks incorporated on a substrate or one or more micro-rings or disks formed on the fiber waveguide itself. Indeed, it is preferable in certain applications for there to be more than one micro-cavity resonator on a single fiber waveguide, for example in creating a multi-wavelength laser array along the fiber waveguide.

The output of the micro-cavity laser of the present invention can be tuned by varying the pump wavelength and/or utilizing different material composition for the micro-cavity optical resonator. In addition, internal structures such as optical gratings can be added to the optical path within the resonator so as preferentially select a particular optical mode for lasing and in turn the frequency. The laser can also be made to operate continuous wave or self-pulsing.

Accordingly, it is an object of the present invention to provide a micro-cavity laser having the advantages detailed herein.

This and other objects of the invention will become apparent to those skilled in the art from a review of the materials contained herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in, and constitute a part of the Specification, illustrate presently known preferred embodiments of the present invention, and together with the proceeding general description and the following Detailed Description, explain the principles of the invention.

In the drawings:

FIGURE 1 is an illustration of a micro-cavity laser of the present invention;

FIGURE 2 is a plan view illustration of a fiber taper and a micro-cavity resonator;

FIGURE 3 is an image of a fiber taper in contact with the equator of a microsphere resonator;

FIGURE 4 is an illustration of a fiber taper coupled with the equator of a microsphere micro-cavity resonator;

FIGURE 5 is a graph illustrating the phase matching of a fiber taper fundamental mode and a microsphere resonator fundamental modes;

FIGURE 6 is an image of the green-up converted photo-luminescence from a fiber taper-pumped microsphere, where the pump wavelength is tuned close to a fundamental whispering gallery mode;

FIGURE 7 is an image of photo-luminescence spectra [taken at point (a) in Figure 8, below] of a microsphere resonator for an annular pump region about the equator. The photo-luminescence (inset) is taken at point (b) in Figure 8 (with a wavelength range matching that of the main spectra), where the side-mode suppression is 26 dB;

FIGURE 8 is a spectral output of collected laser output power versus absorbed pump power in the microsphere (L_{out} - L_{in}). Inset, spectral output of a Fabry-Perot filter, showing the single-mode nature of the micro-cavity laser of the present invention, where for reference a single-frequency laser with a known line-width of 300 kHz is also shown; and

FIGURE 9 shows (a) a single sphere system, and (b) a bi-sphere system in which two spheres have been placed on the same taper and pumped by a single 980 nm laser source, producing two separate laser lines, at 1533 and 1535 nm.

DETAILED DESCRIPTION OF THE INVENTION

Referring hereafter to the figures generally, and in particular to Figures 1-2 here, the present invention is a compact and highly efficient laser 2. In its preferred embodiment, the present invention utilizes transmission media 4; high-Q micro-cavity optical resonators 6; active media associated with the optical resonators to facilitate the lasing of a signal within a frequency band of interest; and, optical pumps to excite the active media. As described below and as will be understood by those skilled in the art, numerous additional implementations of this structure and/or method can be made without departing from the scope or spirit of the invention as described herein.

The transmission media 4 is preferably a fiber waveguide 5 of any type. This includes, without limitation, cylindrical, elliptical, etched, "D"-shape and "panda" fiber configurations as well as polished fiber half-blocks. In the preferred embodiment, a fiber taper 12 is provided in the fiber waveguide 5 between a first and second end of the fiber waveguide 5 as is best illustrated in Figure 2. The tapered sections, 15, 16 and intermediate waist region 14 of the waveguide may be provided, as is known, by stretching the waveguide under controllable tension as it is softened by one or more fixed or movable heat sources (*e.g.*, torches). Commercially available machines can be used for this purpose in production environments. The consequent reduction in diameter of about one or more

orders of magnitude reduces the central core in the core/cladding structure of the optical fiber to vestigial size and function, such that the core no longer serves to propagate the majority of the wave energy. Instead, without significant loss, the wave power in the full diameter fiber transitions into the waist region, where power is confined both within the attenuated cladding material and within a field emanating into the surrounding environment. After propagating through the waist region 14, exterior wave power is recaptured in the diverging tapered region 16 and is again propagated with low loss within the outgoing fiber section 18, as illustrated in Figures 1 and 2.

The high Q resonator 6 in this example is coupled to the externally guided power about the waist region 14 of the waveguide. That is, at all times there is a coupling interaction from the principal fiber into the interior of the resonator 6 via the resonator periphery. The resonator 6 additively recirculates the energy with low loss in the whispering gallery mode ("WGM" or WG mode"), returning a part of the power to the waveguide at the waist 14. When a resonance exists at the chosen wavelength, the resonator 6 functions with effectively total internal reflection and with minimal internal attenuation and radiative losses. However, the emanating portion of the wave power is still confined and guided, so it is presented for coupling back into the waveguide waist 14. Extremely high Q values (as much as 8 billion have been observed) exist in this whispering gallery mode. Different WGM devices can be used for the present invention, including disks, rings, polygons, oblate and prolate spheroids. Furthermore, concentricity or approximate concentricity may in some instances not be necessary, since the WGM effect can exist in non-concentric boundary structures such as ellipses or race-track structures.

In the present invention, the resonator 6 is preferably constructed from a silica material. This provides the advantage of being compatible with many waveguide structures, most importantly, telecommunication fiber waveguides currently in use. Alternatively, resonators can be constructed in a semiconductor, utilizing any of the resonator configurations (*e.g.*, disks, rings, polygons, oblate and prolate spheroids) discussed herein. Depending on the application in which the laser of the present invention might serve and/or the desired frequency bandwidth of the output, the material from which the resonator is constructed may also include one or more additives (for example and without limitation, phosphate) intended to suppress undesirable higher order modes and/or resonances in the resonator 6 at frequencies outside of the desired output bandwidth.

In order for the micro-cavity resonator 6 to lase within a desired frequency bandwidth, an active media must also be present. The active media produces the optical gain necessary to permit lasing once excitation of the structure is initiated by one or more optical pump sources. In the preferred embodiments, the present invention utilizes one or more dopants in the resonator 6 to serve as the active media. The preferred dopants include rare earth materials and particularly erbium, ytterbium, praseodymium, neodymium, holmnium, and thulium, either alone or in combination with another dopant. The exact combination and concentration of dopants depends on the wavelength band or bands sought to be included in the output of the laser of the present invention.

The present invention also utilizes an alignment structure in order to secure the position of the fiber waveguide 6 relative to the micro-cavity resonator 20. Many types of alignment structures are known to those of ordinary skill in the art and may include, without limitation, an etched

substrate or the like. In addition, an alignment structure may include structures of the type disclosed in pending U.S. Patent Application _________, the disclosure of which is incorporated herein in full by reference. Illustrations of these and other embodiments are set forth in Vahala, et al., U.S. Patent Application entitled "Resonant Optical Filters", Serial No. ________, filed February 16, 2001, the disclosure of which is incorporated herein by reference.

To induce a lasing action in the present invention, an excitation signal must be provided to the resonator 6. In the first preferred embodiment, an optical pump 20 is provided to deliver the excitation signal to the resonator 6. Alternative schemes of delivering an excitation sources (*e.g.*, and without limitation, by beam excitation including guided or unguided electrical and/or unguided light beams) can be employed without departing from the scope of the present invention.

Without limiting the foregoing, in the first preferred embodiment an optical pump 20 is optically connected to a first end of the fiber waveguide 5. The optical pump 20 transmits a signal along the waveguide 5 and to the resonator 6 through the fiber taper 12 as discussed above. One or more excited laser signals in the resonator 6 are then communicated to the fiber waveguide 5 propagating both in the direction of the second end of the waveguide as illustrated in Figure 5 (and towards the first end of the waveguide). In an alternative embodiment where the resonator is constructed from a semiconductor, the resonator 6 is preferably pumped by an electrical excitation signal rather than an optical signal, however, pumping in this configuration by a guided or unguided optical or alternative signal beam is also intended to be included within the scope of the present invention.

A significant advantage of the present invention over the work of others is the ability to couple directly to and from optical fiber. Important to this coupling is the ability to "phase match" the fiber taper 12 and the resonator structure 6 to maximize the coupling efficiency. This is done by proper selection of the diameter of the fiber taper 12 at the waist region 14. In so doing, it is possible to match the effective indexes of the fundamental taper mode and the fundamental mode of the resonator 6 (*i.e.*, "phase matching"). As illustrated in Figure 5, where the resonator 6 is a microsphere 7, a 50 micron diameter microsphere 7 phase matches a 1.38 micron diameter fiber taper 12. In the present invention, it is possible to demonstrate critical coupling with 26-dB on-resonance extinction and a matched dual-taper add–drop filter with less than 0.5% scattering loss and near-unity power transfer (on-resonance) between a fiber taper 12 and a micro-cavity resonator 6, where the resonator is a microsphere resonator 7.

A laser of the present invention has been constructed and tested in the laboratory, and is described more fully below. It will be appreciated that this embodiment is but one of many embodiments of the invention disclosed and claimed herein and is described as the currently known best mode of the present invention rather than as a limitation of the invention itself.

In this embodiment and referring to all of the figures generally, a fiber taper 12 is placed in contact with Er:Yb-doped phosphate glass microsphere 9, to form a compact, low-threshold 1.5 mm wavelength fiber laser source. A single fiber taper 12 is used to guide the pump 20 laser beam to the surface of the microsphere 9, resonantly couple the pump 20 into the sphere 9, and then collect the resulting laser emission. The use of a fiber taper 12 not only provides an efficient input and

output coupling port but also plays an important role in producing single-mode lasing. Finally, the fiber taper 12 forms a natural backbone for connecting a series of different active and passive micro-cavity devices, with each device addressing a different wavelength signal. These additional micro-cavity devices can be resonators, modulators, add/drop filters, slicers, or any other device which can optically connected to the fiber waveguide 5, preferably through the fiber taper 12 or one or more additional fiber tapers on the fiber waveguide 5 so as to make such connections without breaking the fiber waveguide 5.

The microspheres used in this embodiment were formed from phosphate glass heavily doped with Yb (20% by weight) and Er (0.5%). Kigre QX/Er phosphate glass has a transformation temperature of 450° C and a refractive index of 1.521 at 1.5 µm. Absorption that is due to the $F_{5/2}$-$F_{7/2}$ transition of the Yb^{3+} ions is strongly peaked around 976nm (±5 nm), with a value of α= 4-5 cm^{-1} (2 X 10^3 dB/m). The $F_{7/2}$ level of Yb^{3+} resonantly couples to the Er^{3+} $I_{11/2}$ level, which then relaxes to the $I_{13/2}$ level. The 1.5-µm lasing transition is between the ground-state $I_{15/2}$ level and the $I_{13/2}$ excited-state level of Er^{3+}, with a fully inverted gain per unit length exceeding 200 dB/m in the 1500 nm band.

Fabrication of the microspheres and the fiber tapers is discussed in the references cited above and incorporated herein. In summary, a small piece of the phosphate glass is melted in a crucible. With the phosphate still molten, the tip of a silica fiber taper, which has a higher melting point, is placed into the melt. As the silica "stem" is extracted, a small phosphate taper is formed on the end of the silica taper. A CO_2 laser is used to melt the end of the phosphate taper, forming a spheroid

under surface tension. The silica fiber stem is finally placed in a fiber chuck and used as a handling rod to control and position the phosphate sphere. It is important to carefully control the temperature of these operations and to cool the sphere quickly in a manner which avoids crystallization of the phosphate in the spheroid to an extent which would interfere with the reflective properties of the spheroid as a micro-cavity optical resonator.

The fiber tapers for this embodiment were formed by taking standard telecommunication 125 μm diameter silica fiber, heating a short region with a torch, and then slowly pulling the fiber ends to form an adiabatic taper region. In order to provide efficient coupling between the fiber taper 12 and the microsphere, a fiber taper diameter must be tailored for each different sphere size and WG mode of interest as described above. Fine tuning of the coupling can further be performed by changing the position of the sphere relative to the taper waist.

The resonant modes of nearly spherical dielectric particles can be classified according to their polarization index p, radial mode number n, and angular mode numbers l and m. Of special interest in this embodiment are the WGM resonances, *i.e.*, those with small radial mode numbers and large angular mode numbers. Excitation of WGMs within glass microspheres 7 via a fiber-taper 12 coupling has several distinct advantages. Most important of these is direct coupling to and from the optical fiber. In addition, alignment is built in, fabrication is relatively simple, and as discussed above, index matching between the fiber taper 12 and the diameter of the WGMs of the microsphere 9 is possible.

A magnified image of a coupled fiber taper microsphere is shown in Figure 3. For the microsphere laser of the present embodiment, the diameter and eccentricity were determined by analysis of its resonant mode structure at 1.5 μm. The measured WG mode free-spectral range in *l* (FSR_l) for this microsphere is 1.1 THz (8.7 nm) at 1.5 μm, giving a diameter of 57 μm. The measured free-spectral range in *m* is 13 GHz for $|m| \approx l$, with the resonant frequencies increasing with decreasing *m* value. This corresponds to a slightly oblate microsphere with an eccentricity of 2.4%. The pump wave in this embodiment is launched from a 980 nm wavelength, narrow-line width (< 300-kHz), tunable external-cavity laser into the fundamental mode of the fiber taper.

As discussed above, this embodiment also maximizes the efficiency of the pumping of the microsphere 9 by providing a good match between the fundamental mode of the fiber taper 12 and the WG modes of the sphere 9 and by matching the input coupling strength to the round-trip resonator loss (*i.e.*, critical coupling). Owing to the large absorption within the microsphere 9 at the pump band and the subsequent large round-trip microsphere resonator loss, maximum power transfer is obtained for the fundamental WG modes ($|m| = l$), as the spatial overlap with the fiber taper 12 is highest for the equatorial modes, resulting in higher input coupling strengths. For this sphere, a taper diameter of 1.75 micrometers was used to phase match and selectively excite the lowest-order ($n = 1,2$) fundamental WG modes of the sphere 9.

The pump volume within the micro-sphere can be obtained from images of the visible photo-luminescence. The green emission is due to spontaneous emission from the up converted $F_{9/2}$ level to the ground state of Er^{3+} and traces the path taken by the 980 nm pump wave within the sphere 9.

The image in Figure 6 shows a ring encircling the equator of the sphere. This equatorial ring corresponds to resonant pumping of a near fundamental WG mode. For this taper–sphere combination, and with resonant pumping of an equatorial WG mode, the scattering loss of the taper–sphere junction is less than 5% (as measured by the off-resonance transmission), and roughly 85% of the pump power is absorbed by the microsphere.

Lasing in the microsphere 9 is rather complex, owing to the large number of high-Q modes that are present in the sphere 9, the spatial selectivity of the pump 20, the loading of the sphere 9 as a result of the taper 12, the large spectral gain bandwidth, and the variations in the emission and absorption cross sections versus wavelength in the phosphate materials. For this reason other resonator geometries such as disks, rings or racetracks may be preferable to obtain a simplified resonator spectrum.

Depending on the gain region within the sphere, lasing occurred at wavelengths ranging from 1530 to 1560 nm in both multimode and single-mode fashion. By adjusting the taper 12 contact position on the sphere 9 and the pump 20 wavelength, it is possible to switch between multi-mode and single-mode lasing action. Single-mode lasing was obtained in this embodiment by tuning the pump wavelength to a fundamental WG mode resonance that produced a narrow equatorial-ring gain region. A typical single-mode lasing spectrum (as collected by the taper 12) for an equatorial-ring pump region is shown in Figure 7. To resolve the fine spectral features of the laser (different m modes) a high-finesse (~10,000) scanning Fabry–Perot cavity with a spectral resolution of a few megahertz was used to obtain the spectra shown in the inset of Figure 8. The microsphere of this

embodiment of the present invention will lase on a single m WG mode over the entire pump range depicted in Figure 8.

This embodiment of the present invention was also self-pulsing under the pump conditions identified herein, with a period of roughly 15 ms and a pulse width of 500 ns. Instability in the output of this embodiment can be linked to the large unpumped highly absorbing regions within the sphere 9 and the nonlinear dynamics associated with absorption saturation. A plot of the laser power collected in the taper 12 versus the total pump power absorbed and scattered by the presence of the sphere 9 (L_{out} - L_{in}) is shown in Figure 8. The lasing threshold for this embodiment in this configuration is estimated at 60μW, and the laser 22 can reach an output power of 3μW while remaining single mode. A collected power as high as 10μW was obtained in a single line at higher pump power, although the laser 22 was multimode. Given that this embodiment and configuration used the same taper 12 as was used to couple in the 980-nm pump power in the earlier described embodiment, to couple out the 1.5 μm laser power from the sphere 9, and since the taper was designed to phase match at the 980 nm pump wavelength to reduce the lasing threshold, the laser emission of this embodiment is not optimally collected by the taper 12. A dual-taper system, as is described earlier and in the Cai and Vahala reference above identified, could be employed to likely improve the differential output efficiency.

A further embodiment is the use of multiple resonators on a single fiber waveguide 5. This ability to cascade a series of devices is illustrated in Figure 9, where two phosphate glass microspheres 21, 23 are positioned along a single fiber taper, one after the other. The micro-cavity

devices can be the same or different sizes, depending on what the use and purpose the cascading is intended to achieve. Figure 9 shows a taper with two different-sized microspheres 21, 23 attached. The laser shown in Figure 9(a) has a wavelength of 1535 nm; the laser shown in Figure 9(b) which has a second microsphere 23 placed in contact with the fiber taper, a second laser line at 1533 nm appears. Thus, utilizing multiple resonators in a single fiber can be used to create a laser array.

Each of the characteristics in the present invention are believed to be new and unique, and are not found in the prior art. While the implementations described below are directed to embodiments of a laser which utilize a tapered fiber and a microsphere resonator, it will be understood by those skilled in the art that such configurations and/or combinations are merely embodiment of the present inventions. Thus, none of the embodiments are intended to be limitations on the scope of the invention described herein and set forth in the claims below.

CLAIMS

We claim:

1. A micro-cavity laser comprising:

a. A fiber waveguide, said fiber waveguide having a tapered coupling region, said tapered coupling region being positioned between said first end and said second end of said fiber waveguide;

b. A micro-cavity optical resonator, said micro-cavity optical resonator being arranged so as to provide optical coupling between said tapered coupling region of said fiber and said micro-cavity optical resonator, said micro-cavity optical resonator having at least one optical resonance at a desired frequency output, said micro-cavity including an active medium capable of providing optical gain upon pump excitation; and,

c. At least one laser pump, the output of said laser pumps being optically connected to said first end of said fiber waveguide to couple optical pump power into said resonator to excite at least one resonance to pump said active medium, and induce lasing action such that laser output power is coupled to said fiber waveguide.

2. A micro-cavity laser of Claim 1 further including a second fiber waveguide, said second fiber waveguide having a coupling region between a first end and a second end of said second

fiber waveguide, said second fiber waveguide being optically coupled to said micro-cavity optical resonator.

3. The micro-cavity laser of Claim 2 further including a second set of at least one laser pumps, the output of at least one of said second set of laser pumps is optically connected to said first end of second fiber waveguide and the output of said second set of laser pumps excites at least one resonance in said micro-cavity optical resonator and thereby pumps the active medium to induce lasing action.

4. The micro-cavity laser of Claim 3 wherein the output of at least one of said second set of laser pumps excites at least one resonance in said micro-cavity optical resonator at a frequency different from the resonance excited by the output of said laser pumps optically connected to said first fiber waveguide.

5. The micro-cavity laser of Claim 2 wherein the said first fiber waveguide and said second fiber waveguide are optically coupled to the same micro-cavity resonances.

6. The micro-cavity laser of Claim 5 wherein the said first fiber waveguide preferentially couples laser pump power from said fiber waveguide to the micro-cavity to attain lasing and

said second fiber waveguide preferentially couples laser output power from said micro-cavity to said second fiber waveguide.

7. The micro-cavity laser of Claim 1 wherein said micro-cavity optical resonator is one of a microsphere, disk, ring, and racetrack.

8. The micro-cavity laser of Claim 1 wherein said micro-cavity is based on silica.

9. The micro-cavity laser of Claim 8 wherein said silica-based micro-cavity is doped with a rare earth element to provide an active medium.

10. The micro-cavity laser of Claim 9 wherein said rare earth element is at least one of erbium, ytterbium, praseodymium, neodymium, holmnium, and thulium.

11. The micro-cavity laser of Claim 1 wherein said micro-cavity optical resonator is a semiconductor, said semiconductor being arranged to be pumped electrically.

12. The micro-cavity laser of Claim 1 wherein the material composition of said micro-cavity includes phosphate glass.

13. The micro-cavity laser of Claim 1 wherein said micro-cavity optical resonator includes a plurality of micro-rings in a semiconductor.

14. The micro-cavity laser of Claim 1 wherein said micro-cavity optical resonator includes a plurality of micro-rings on an optical fiber.

15. The micro-cavity laser of Claim 1 wherein said micro-cavity optical resonator includes a plurality of photonic crystal cavities.

16. The micro-cavity laser of Claim 1 wherein said micro-cavity optical resonator is fabricated on a substrate.

17. The micro-cavity laser of Claim 1 wherein the micro-cavity optical resonator includes Bragg gratings in the resonant mode path so as to provide increased spectral purity of the lasing output.

18. The micro-cavity laser of Claim 17 wherein the Bragg gratings in the resonant mode path are defined holographically.

19. The micro-cavity laser of Claim 1 wherein the micro-cavity optical resonator has at least one preferred output frequency, and further including a frequency selector in the mode path of the micro-cavity optical resonator of at least one of the preferred output frequencies of the micro-cavity optical resonator.

20. A system for producing laser emission in a desired wavelength band, the system comprising:

a. A fiber waveguide, said waveguide having a first end and a second end and a tapered region therebetween, said tapered region having a tapered diameter;

b. A micro-cavity optical resonator, said resonator having a mode path diameter, said micro-cavity resonator being constructed from a silica material doped with at least one dopant;

c. Optical gratings, said optical gratings being position in the mode path of at least one resonant frequency of said micro-cavity optical resonator;

d. An alignment structure, said alignment structure being arranged to locate said micro-cavity optical resonator and said fiber waveguide in proximity to one another so as to enable coupling between said tapered region of said fiber waveguide and said micro-cavity optical resonator; and,

e. A laser pump, said laser pump being optically connected to said first end of said fiber waveguide and being arranged so as to launch one or more signals into said fiber

waveguide, said optical pump signals having frequencies which excite resonances in the micro-cavity optical resonator to thereby pump at least one silica dopant to induce lasing emission within a desired output frequency band of the system.

21. The system of Claim 20 wherein at least one of the laser pump source signals is in the 980 nanometer emission band.

22. The system of Claim 20 wherein the lasing emission is in the range of 1300-1600 nanometers.

23. The system of Claim 22 wherein the output of the system is used in a telecommunications application.

24. The system of Claim 20 wherein said taper section diameter and said mode path diameter are selected to provide optimal phased matching such that the coupling efficiency for pump and laser emission is maximized.

25. The system of Claim 20 wherein said fiber waveguide includes at least one additional optical resonator optically coupled thereto at the tapered section. Said at least one additional optical

resonator doped so as to enable operation as a laser and optically pumped by coupling to said fiber waveguide.

26. The system of Claim 25 wherein said fiber waveguide has at least one additional taper coupling sections therein and at least one of said additional doped resonators is coupled to at least one of said additional taper sections in said fiber waveguide.

27. The system of Claim 20 wherein the system includes at least one additional fiber waveguide, each said additional fiber waveguide is optically coupled to said micro-cavity resonator and arranged so as to permit additional laser pumping of or laser emission coupling from said micro-cavity optical resonator.

28. The laser of Claim 20 wherein said micro-cavity is a sphere, disk, ring or racetrack.

29. The system of Claim 20 wherein optical gratings increase the spectral purity of the laser emission by forcing laser oscillation at a desired frequency.

30. The system of Claim 20 wherein said dopants include at least one of erbium, ytterbium, praseodymium, neodymium, holmnium, and thulium.

31. The system of Claim 20 wherein said fiber waveguide is a panda fiber.

32. A micro-cavity laser comprising:

a. A first fiber waveguide, said first fiber waveguide having an evanescent coupling region, said evanescent coupling region being positioned between a first end and a second end of said fiber waveguide;

b. A micro-cavity optical resonator, said micro-cavity optical resonator being positioned in proximity to said coupling region of said first fiber so as to evanescently couple said fiber coupling region and said micro-cavity optical resonator, said micro-cavity optical resonator having at least one optical resonance at a desired frequency output, said micro-cavity optical resonator comprising an active medium capable of providing optical gain when excited; and

c. A laser pump, said laser pump being optically connected to said first end of said fiber waveguide for the purpose of exciting said gain medium.

33. The laser of Claim 32 wherein said micro-cavity resonator is fabricated on a chip or substrate.

34. The laser of Claim 33 wherein said fiber waveguide is an etched fiber.

35. The system of Claim 33 wherein said fiber waveguide is a D-fiber.

36. The system of Claim 33 wherein said fiber waveguide includes polished fiber half-blocks.

37. The system of Claim 33 wherein said fiber waveguide is a panda fiber.

38. The system of Claim 33 wherein said waveguide coupling section is phased matched to said resonator such that the pump coupling and laser emission collection efficiency are maximized.

39. The micro-cavity laser of Claim 33 wherein the micro-cavity optical resonator has at least one preferred output frequency, and further including frequency modifier gratings, said gratings being disposed in the mode path of the micro-cavity optical resonator of at least one of the preferred output frequencies of the micro-cavity optical resonator.

40. The micro-cavity laser of Claim 33 wherein said micro-cavity optical resonator includes at least one of a micro-disk, ring and racetrack.

41. A micro-cavity laser comprising:

a. A fiber waveguide, said waveguide having a first end and a second end and a tapered region therebetween, said tapered region having a tapered diameter;

b. A highly doped Erbium:Ytterbium phosphate silica micro-sphere, said microsphere being arranged so as to enable weak optical coupling between said microsphere and said tapered region of said fiber waveguide; and

c. A laser pump signal, said laser pump signal being transmitted in said fiber waveguide through said tapered region, said laser signal including a frequency which excites a resonance in said silica microsphere and pumps the erbium gain medium to induce laser emission.

42. A micro-cavity laser system comprising:

a. A fiber waveguide, said fiber waveguide having at least one tapered coupling region, said tapered coupling regions being located between said first end and said second end of said fiber waveguide;

b. A plurality of micro-cavity optical resonators including a first micro-cavity resonator, each said micro-cavity optical resonator being arranged in proximity to at least one of said tapered coupling regions so as to provide optical coupling between said micro-cavity optical resonator and said fiber waveguide through at least one said tapered coupling region of said fiber waveguide, at least one of said micro-cavity

optical resonators having at least one optical resonance at a desired frequency output, said first micro-cavity optical resonator including an active medium associated therewith capable of providing optical gain upon pump excitation; and

c. At least one laser pump, the output of said laser pump being optically connected to said first end of said fiber waveguide to couple optical pump power into at least said first micro-cavity resonator to excite said active medium associated with said first micro-cavity optical resonator and induce lasing action such that laser output power is coupled to said fiber waveguide.

43. The micro-cavity laser system of Claim 42 wherein the laser system includes at least a second micro-cavity optical resonator, said at least a second micro-cavity resonator including an active medium, said active medium associated with said at least a second micro-cavity optical resonator providing optical gain upon pump excitation at a frequency different than in said first micro-cavity optical resonator.

44. The micro-cavity laser system of Claim 42 wherein at least one of said micro-cavity optical resonators is one of a microsphere, disk, ring, and racetrack.

45. The micro-cavity laser system of Claim 42 wherein said micro-cavity is based on silica.

46. The micro-cavity laser system of Claim 45 wherein said silica-based micro-cavity is doped with a rare earth element to provide an active medium.

47. The micro-cavity laser system of Claim 46 wherein said rare earth element is at least one of erbium, ytterbium, praseodymium, neodymium, holmnium, and thulium.

48. The micro-cavity laser system of Claim 42 wherein said plurality of micro-cavity optical resonators are semiconductor based, said semiconductor being arranged to be pumped electrically.

49. The micro-cavity laser system of Claim 42 wherein the material composition of at least one micro-cavity resonator includes phosphate glass.

50. The micro-cavity laser of Claim 42 wherein said plurality of micro-cavity optical resonators are fabricated on a substrate.

51. The micro-cavity laser system of Claim 42 wherein said plurality of micro-cavity optical resonator includes a plurality of micro-rings on an optical fiber.

52. The micro-cavity laser system of Claim 42 wherein said plurality of micro-cavity optical resonator includes a plurality of photonic crystal cavities.

53. The micro-cavity laser system of Claim 42 wherein said plurality of micro-cavity optical resonator is fabricated on a substrate material which is a semiconductor.

54. A method of creating a laser signal of a desired frequency, the steps comprising:

Launching at least one signal into a fiber waveguide, said waveguide having a tapered coupling region, said tapered coupling region being optically coupled to a micro-cavity resonator, said micro-cavity resonator containing a gain medium and being resonant and critically coupled to the signal so as to permit excitation of the gain medium and lasing in a desired emission band.

55. A method of obtaining a laser signal within a desired frequency range, the steps comprising:

Receiving a laser signal in a waveguide, said waveguide being optically connected to a fiber waveguide, said fiber waveguide having a fiber tapered coupling region therein, said tapered coupling region being optically coupled to a micro-cavity resonator, said micro-cavity resonator having a resonance at the desired output

frequency, and said micro-cavity resonator containing a gain medium capable of amplification at the desired output frequency and excitation from the said laser signal.

56. A method of fabricating a phosphorus glass microsphere for use in a micro-cavity resonator, the steps comprising:

Melting a small piece of phosphorus glass material in a crucible,

Stabilizing the temperature of said molten phosphorus glass,

Placing the tip of a silica fiber taper into the molten phosphorus glass,

Extracting the silica fiber so that a small phosphate taper is formed on the end of the silica fiber taper;

Melting the end of the phosphate taper until a spheroid forms under surface tension,

Quickly cooling the phosphate sphere in a manner which avoids crystallization of the phosphate in the spheroid to an extent which would interfere with the refractive properties of the spheroid as a micro-cavity optical resonator.

57. The method of producing a microsphere of Claim 54 wherein said phosphorus glass material is doped with a rare earth element.

58. The method of Claim 55 wherein said dopant includes Erbium.

59. The method of Claim 55 wherein said dopant includes Ytterbium.

ABSTRACT

The present invention is a micro-cavity laser and methods related thereto. In the preferred embodiments, the micro-cavity laser comprises a laser pump signal in a fiber waveguide which is optically coupled to a micro-cavity resonator through a fiber taper. The micro-resonator includes a gain medium necessary for lasing action. The lasing frequency can be determined based upon the gain medium, the micro-cavity structure, as well as frequency selective elements such as gratings incorporated into the micro-cavity. The tapered fiber waveguide permits the micro-cavity laser to operate without a break in the fiber waveguide. In the preferred embodiments, the micro-cavity resonator is constructed from a doped silica or a semiconductor material. The present invention provides a compact laser with improved emissions and coupling efficiencies. Alternative configurations include multiple micro-cavities on a single fiber waveguide and/or utilizing multiple waveguides attached to one or more micro-cavity resonators. The laser can be made to operate in a continuous-wave as opposed to self-pulsing mode.

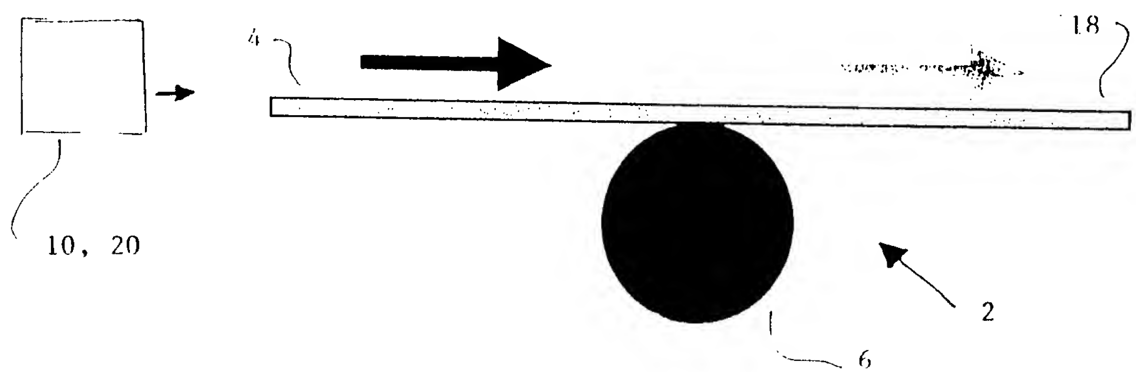


FIGURE 1

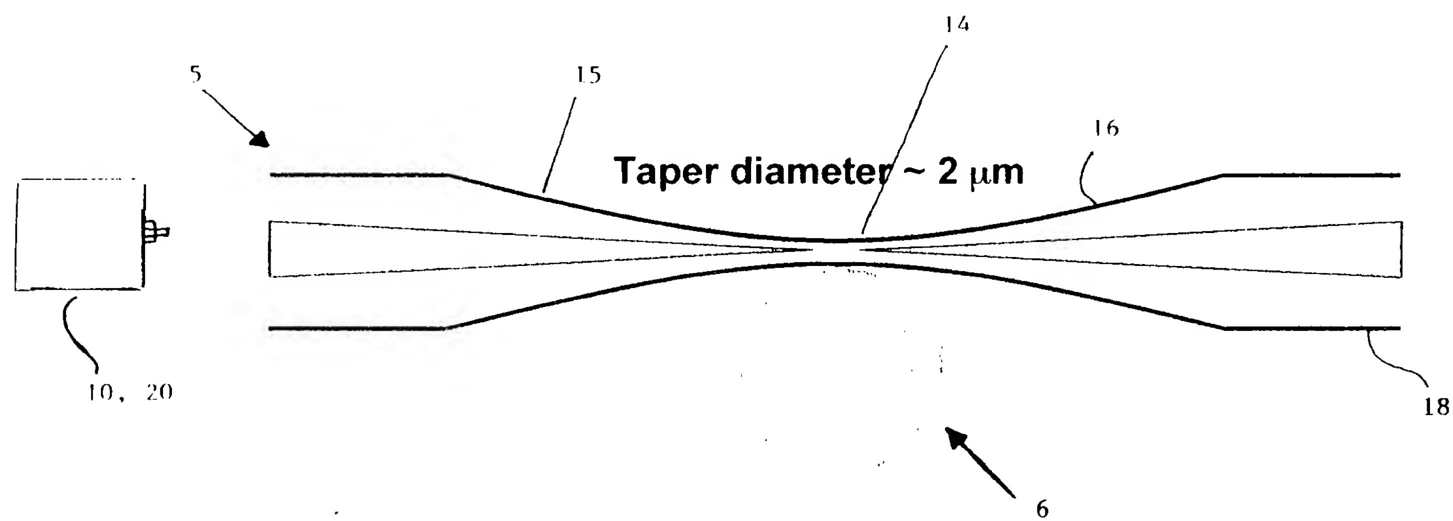


FIGURE 2

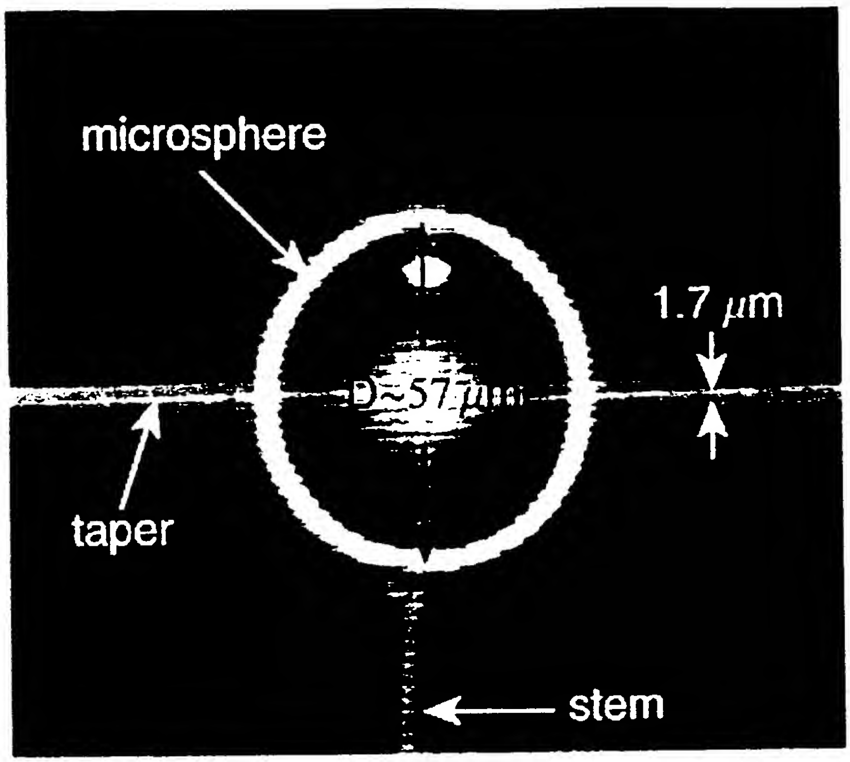


FIGURE 3

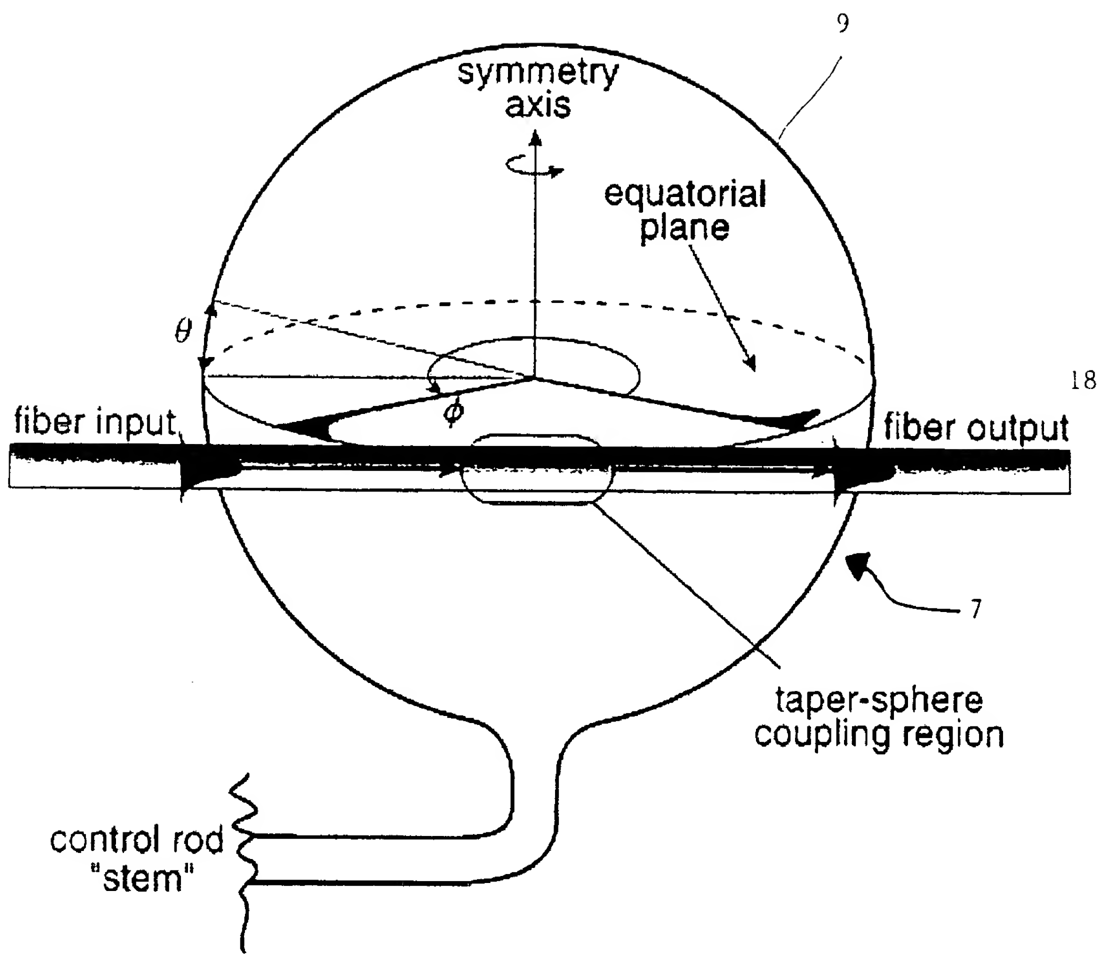
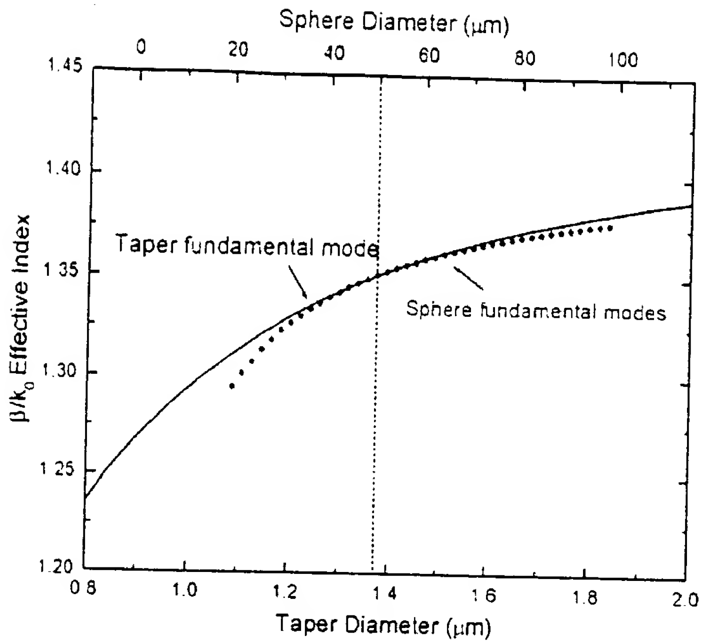

9
symmetry
axis
equatorial
plane
θ
18
fiber input
ϕ
fiber output
7
taper-sphere
coupling region
control rod
"stem"

FIGURE 4



Sphere Diameter (μm)
0
20
40
60
80
100
1.45
1.40
1.35
1.30
1.25
1.20
β/k0 Effective Index
Taper fundamental mode
Sphere fundamental modes
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Taper Diameter (μm)

FIGURE 5

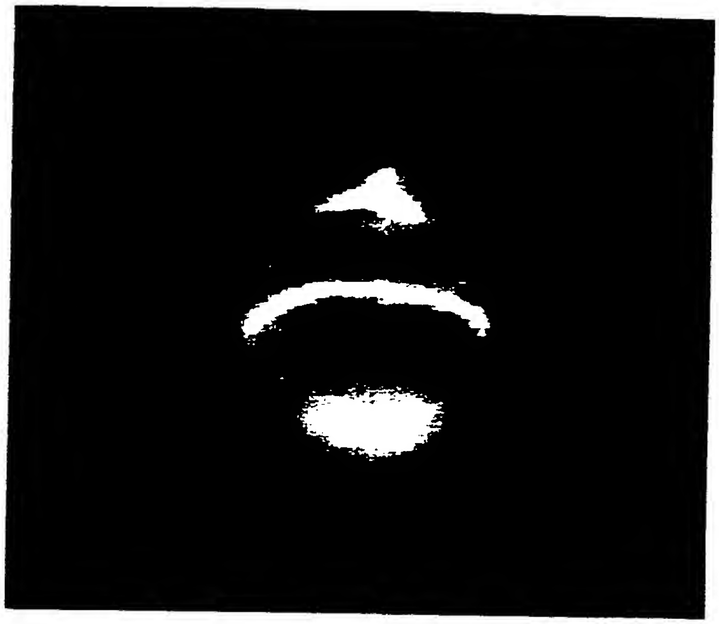
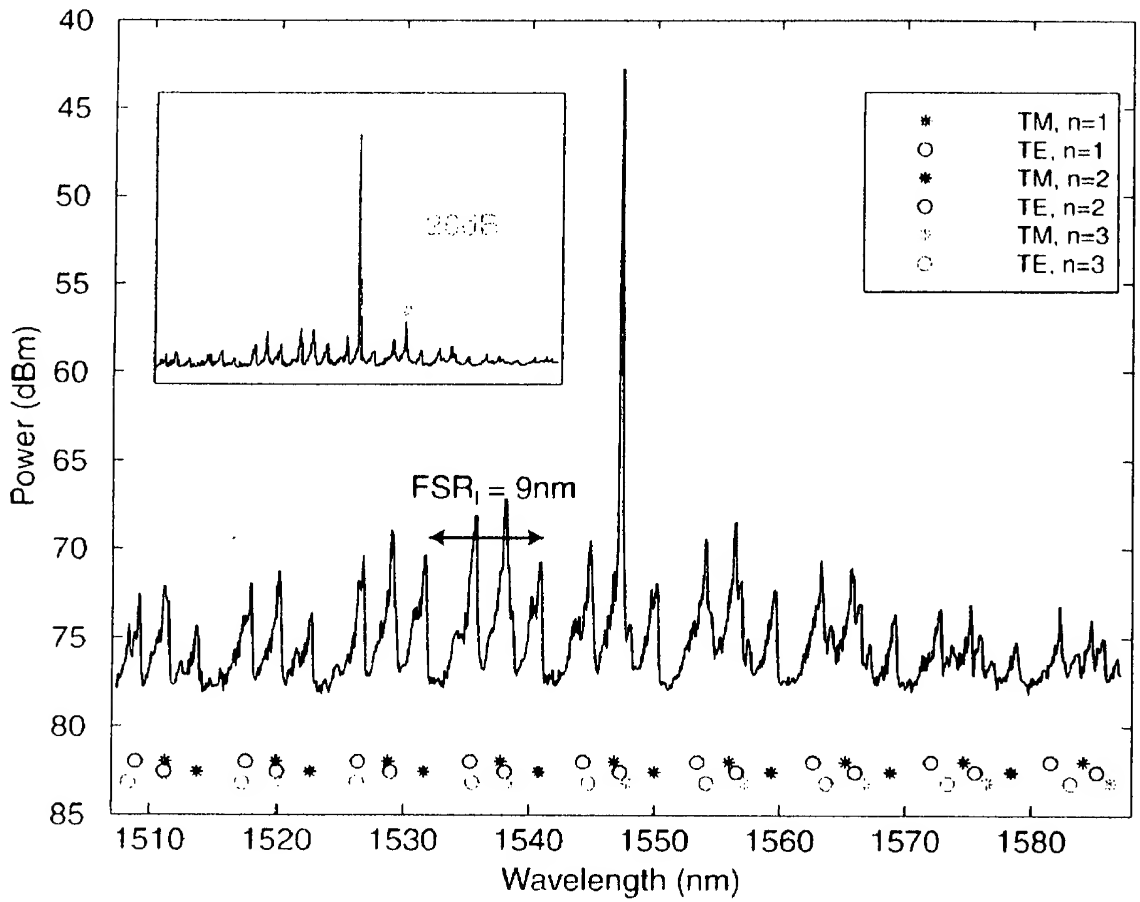
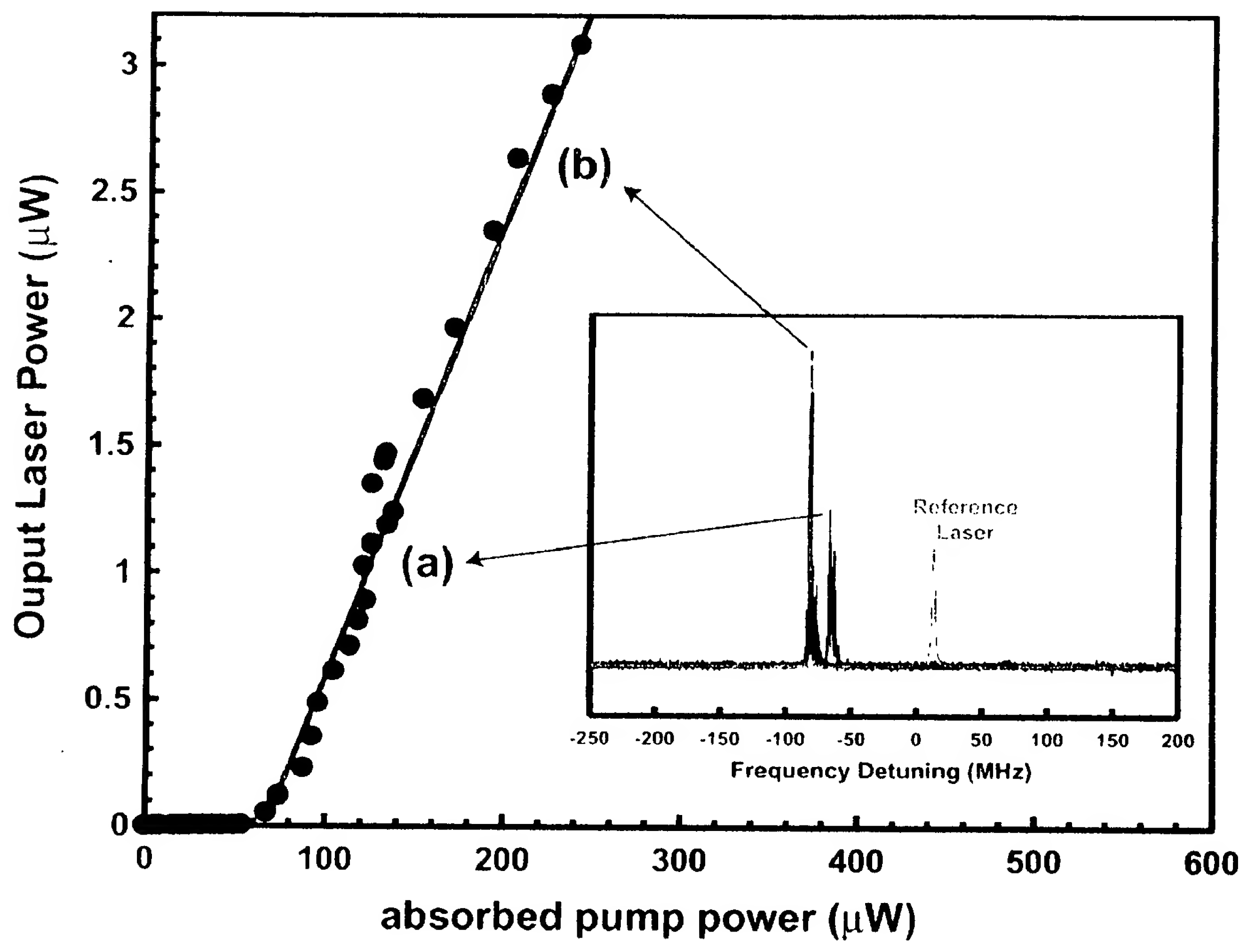


FIGURE 6



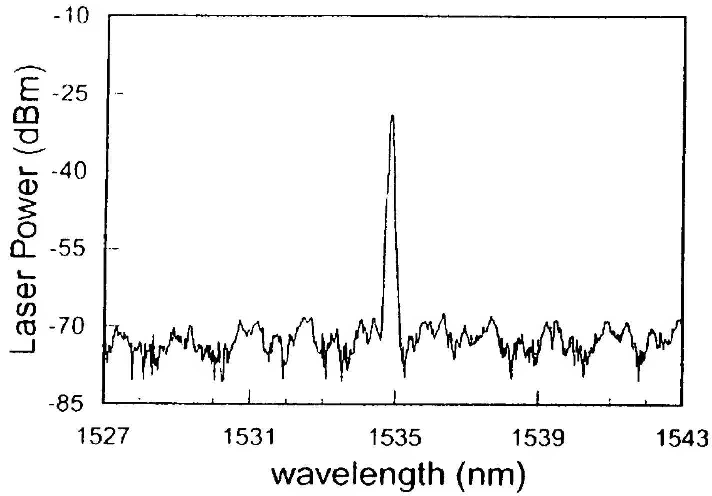
40
45
50
55
60
65
70
75
80
85
Power (dBm)
1510
1520
1530
1540
1550
1560
1570
1580
Wavelength (nm)
FSR$_l$ = 9nm
TM, n=1
TE, n=1
TM, n=2
TE, n=2
TM, n=3
TE, n=3

FIGURE 7



Ouput Laser Power (μW)
absorbed pump power (μW)
0
0.5
1
1.5
2
2.5
3
0
100
200
300
400
500
600
(a)
(b)
Reference
Laser
-250
-200
-150
-100
-50
0
50
100
150
200
Frequency Detuning (MHz)

FIGURE 8



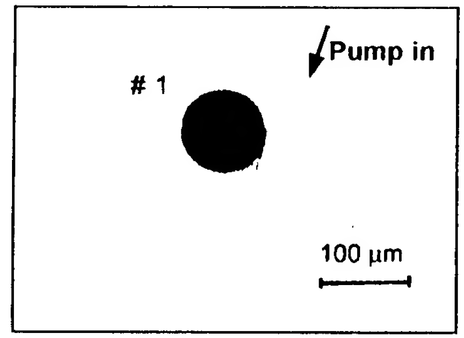
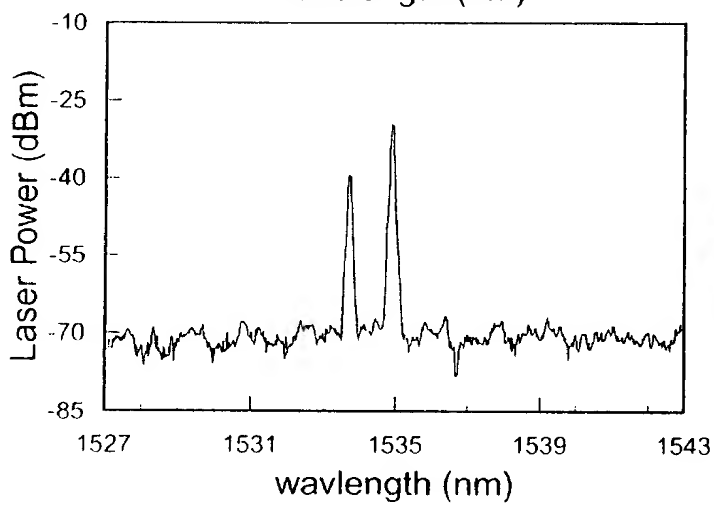


FIGURE 9(a)



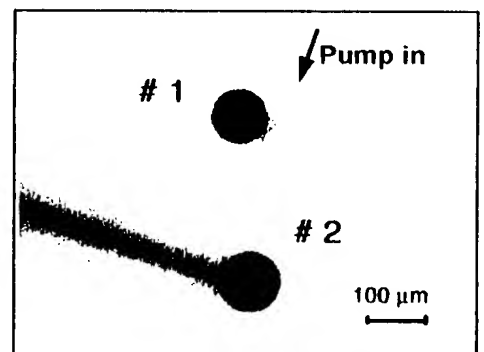


FIGURE 9(b)

FIGURE 9

VERIFIED STATEMENT CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) & 1.27(d))—NONPROFIT ORGANIZATION	Docket Number (Optional) 6/081

Applicant or Patentee: Oskar PAINTER, et al.
Serial or Patent No.: ______
Filed or Issued: ______
Title: MICRO-CAVITY LASER

I hereby declare that I am an official empowered to act on behalf of the nonprofit organization identified below:
NAME OF NONPROFIT ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY
ADDRESS OF NONPROFIT ORGANIZATION 1200 East California Boulevard, Pasadena, California 91125, USA

TYPE OF NONPROFIT ORGANIZATION:

☐ UNIVERSITY OR OTHER INSTITUTION OF HIGHER EDUCATION

☐ TAX EXEMPT UNDER INTERNAL REVENUE SERVICE CODE (26 U.S.C. 501(a) and 501(c)(3))

☐ NONPROFIT SCIENTIFIC OR EDUCATIONAL UNDER STATUTE OF STATE OF THE UNITED STATES OF AMERICA
(NAME OF STATE ______)
(CITATION OF STATUTE ______)

☐ WOULD QUALIFY AS TAX EXEMPT UNDER INTERNAL REVENUE SERVICE CODE (26 U.S.C. 501(a) AND 501(c)(3)) IF LOCATED IN THE UNITED STATES OF AMERICA

☐ WOULD QUALIFY AS NONPROFIT SCIENTIFIC OR EDUCATIONAL UNDER STATUTE OF STATE OF THE UNITED STATES OF AMERICA IF LOCATED IN THE UNITED STATES OF AMERICA
(NAME OF STATE ______)
(CITATION OF STATUTE ______)

I hereby declare that the nonprofit organization identified above qualifies as a nonprofit organization as defined in 37 CFR 1.9(e) for purposes of paying reduced fees to the United States Patent and Trademark Office regarding the invention described in:

☐ the specification filed herewith with title as listed above.
☐ the application identified above.
☐ the patent identified above.

I hereby declare that rights under contract or law have been conveyed to and remain with the nonprofit organization regarding the above identified invention. If the rights held by the nonprofit organization are not exclusive, each individual, concern or organization having rights in the invention must file separate verified statements swearing to their status as small entities and that no rights to the invention are held by any person, other than the inventor, who would not qualify as an independent inventor under 37 CFR 1.9(c) if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a non profit organization under 37 CFR 1.9(e).

Each person, concern or organization having any rights in the invention is listed below:

☐ no such person, concern, or organization exists.
☐ each such person, concern or organization is listed below.

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b)).

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF PERSON SIGNING Kerry Vahala, Professor

TITLE IN ORGANIZATION OF PERSON SIGNING CALIFORNIA INSTITUTE OF TECHNOLOGY

ADDRESS OF PERSON SIGNING 1200 East California Boulevard, Pasadena, California 91125, USA

SIGNATURE ______ DATE ______

STATEMENT CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) & 1.27(c))--SMALL BUSINESS CONCERN

Docket Number 6/081

Applicant, Patentee, or Identifier: Oskar PAINTER, Ming CAI, Kerry VAHALA and Peter C. SERCEL

Application or Patent No.: ______

Filed or Issued: 09 March 2001

Title: **MICRO-CAVITY LASER**

I hereby state that I am

☐ the owner of the small business concern identified below:

☒ an official of the small business concern empowered to act on behalf of the concern identified below:

NAME OF SMALL BUSINESS CONCERN ALEPH LIGHTGATE CORPORATION

ADDRESS OF SMALL BUSINESS CONCERN 427 E. Huntington Drive
Monrovia, California 91016
United States of America

I hereby state that the above identified small business concern qualifies as a small business concern as defined in 13 CFR Part 121 for purposes of paying reduced fees to the United States Patent and Trademark Office. Questions related to size standards for a small business concern may be directed to: Small Business Administration, Size Standards Staff, 409 Third Street, SW, Washington, DC 20416.

I hereby state that rights under contract or law have been conveyed to and remain with the small business concern identified above with regard to the invention described in:

☒ the specification filed herewith with title as listed above.

☐ the application identified above.

☐ the patent identified above.

If the rights held by the above identified small business concern are not exclusive, each individual, concern, or organization having rights in the invention must file separate statements as to their status as small entities, and no rights to the invention are held by any person, other than the inventor, who would not qualify as an independent inventor under 37 CFR 1.9(c) if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d), or a nonprofit organization under 37 CFR 1.9(e).

Each person, concern, or organization having any rights in the invention is listed below:

☐ no such person, concern, or organization exists.

☒ each such person, concern, or organization is listed below.

Separate statements are required from each named person, concern or organization having rights to the invention stating their status as small entities. (37 CFR 1.27)

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

NAME OF PERSON SIGNING Peter C. Sercel

TITLE OF PERSON IF OTHER THAN OWNER President

ADDRESS OF PERSON SIGNING 427 E. Huntington Drive
Monrovia, California 91016
United States of America

SIGNATURE ______ DATE ______

::ODMA\MHODMA\LADOCS;411469;1

Attorney Docket No. 6,081

ASSIGNMENT

(1-8)	*Insert Name(s) of Inventor(s)*	(1)	**Oskar PAINTER**	(5)	
		(2)	**Ming CAI**	(6)	
		(3)	**Kerry VAHALA**	(7)	
		(4)	**Peter C. SERCEL**	(8)	

In consideration of the sum of one dollar ($1.00) and other good and valuable considerations paid to each of the undersigned, the undersigned agree(s) to assign, and hereby does assign, transfer and set over to

(9)	*Insert name of Assignee*	(9)	ALEPH LIGHTGATE CORPORATION
(10)	*Insert state of Incorporation of Assignee*	(10)	A California Corporation
(11)	*Insert address of Assignee*	(11)	of 427 E. Huntington Drive Monrovia, California 91016 United States of America

(hereinafter designated as the Assignee) the entire worldwide right, title and interest in the invention known as

(12)	*Insert identification of Invention, such as Title, Case Number or Foreign Application Number*	(12)	**MICRO-CAVITY LASER**

for which the undersigned has (have) executed an application for patent in the United States of America and all patent applications in foreign countries corresponding thereto or based thereon.

(13)	*Insert Date of Signing of Application*	(13)	on

1) The undersigned agree(s) to execute all papers necessary in connection with any original, reissue, divisional and continuing United States and foreign applications for the above-identified invention and also to execute separate assignments in connection with such applications as the Assignee may deem necessary or expedient.

2) The undersigned agree(s) to execute all papers necessary in connection with any interference which may be declared concerning this application or continuation or division thereof and to cooperate with the Assignee in every way possible in obtaining evidence and going forward with such interference.

3) The undersigned agree(s) to execute all papers and documents and perform any act which may be necessary in connection with claims or provisions of the International Convention for Protection of Industrial Property or similar agreements.

4) The undersigned agree(s) to perform all affirmative acts which may be necessary to obtain a grant of a valid United States patent to the Assignee.

5) The undersigned hereby authorize(s) and request(s) the Commissioner of Patents to issue any and all Letters Patents of the United States resulting from said application or any division or divisions or continuing applications thereof to the said Assignee, as Assignee of the entire interest, and hereby covenants that he has (they have) full right to convey the entire interest herein assigned, and that he has (they have) not executed any agreement in conflict herewith.

6) The undersigned hereby appoints SCOTT MILLER, Reg. No. 32,278, SHARMINI N. GREEN, Reg. No. 41,410 and DENNIS S. MORRIS, Reg. No. 38,975 the power to insert on this assignment any further identification which may be necessary or desirable in order to comply with the rules of the United States Patent and Trademark Office for recordation of this document.

Date	______________	Signature of Inventor **Oskar PAINTER**	______________
Date	______________	Signature of Inventor **Ming CAI**	______________
Date	______________	Signature of Inventor **Kerry VAHALA**	______________
Date	______________	Signature of Inventor **Peter C. SERCEL**	______________

ASSIGNMENT

(1-8)	*Insert Name(s) of Inventor(s)*	(1)	**Oskar PAINTER**	(5)
		(2)	**Ming CAI**	(6)
		(3)	**Kerry VAHALA**	(7)
		(4)	**Peter C. SERCEL**	(8)

In consideration of the sum of one dollar ($1.00) and other good and valuable considerations paid to each of the undersigned, the undersigned agree(s) to assign, and hereby does assign, transfer and set over to

(9)	*Insert name of Assignee*	(9)	**CALIFORNIA INSTITUTE OF TECHNOLOGY**
(10)	*Insert state of Incorporation of Assignee*	(10)	A California Corporation
(11)	*Insert address of Assignee*	(11)	of 1200 East California Boulevard Pasadena, California 91124, USA

(hereinafter designated as the Assignee) the entire worldwide right, title and interest in the invention known as

(12)	*Insert identification of Invention, such as Title, Case Number or Foreign Application Number*	(12)	**MICRO-CAVITY LASER** for which the undersigned has (have) executed an application for patent in the United States of America and all patent applications in foreign countries corresponding thereto or based thereon.
(13)	*Insert Date of Signing of Application*	(13)	on

1) The undersigned agree(s) to execute all papers necessary in connection with any original, reissue, divisional and continuing United States and foreign applications for the above-identified invention and also to execute separate assignments in connection with such applications as the Assignee may deem necessary or expedient.

2) The undersigned agree(s) to execute all papers necessary in connection with any interference which may be declared concerning this application or continuation or division thereof and to cooperate with the Assignee in every way possible in obtaining evidence and going forward with such interference.

3) The undersigned agree(s) to execute all papers and documents and perform any act which may be necessary in connection with claims or provisions of the International Convention for Protection of Industrial Property or similar agreements.

4) The undersigned agree(s) to perform all affirmative acts which may be necessary to obtain a grant of a valid United States patent to the Assignee.

5) The undersigned hereby authorize(s) and request(s) the Commissioner of Patents to issue any and all Letters Patents of the United States resulting from said application or any division or divisions or continuing applications thereof to the said Assignee, as Assignee of the entire interest, and hereby covenants that he has (they have) full right to convey the entire interest herein assigned, and that he has (they have) not executed any agreement in conflict herewith.

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Date	______________	Signature of Inventor **Oskar PAINTER**	______________
Date	______________	Signature of Inventor **Ming CAI**	______________
Date	______________	Signature of Inventor **Kerry VAHALA**	______________
Date	______________	Signature of Inventor **Peter C. SERCEL**	______________

DECLARATION
and POWER OF ATTORNEY

☒ ORIGINAL

☐ CONTINUATION

☐ DIVISIONAL

As a below named inventor, I declare that the information given herein is true, that I believe that I am the original, first and sole inventor (if only one name is listed as 1 below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

MICRO-CAVITY LASER

the specification of which is attached hereto unless the following box is checked:

☐ was filed on ____________ as United States Patent Application Number   or PCT International Application Number

and was amended on   .

My residence, post office address and citizenship are as stated below next to my name.

I acknowledge my duty to disclose information which is material to the patentability of this application in accordance with Title 37, Code of Federal Regulations §1.56(a).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I hereby claim foreign priority benefits under Title 35, United States Code, § 119 of any foreign applications(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

N/A

COUNTRY	APPLICATION NUMBER	DATE OF FILING Month Day Year	PRIORITY CLAIMED UNDER 35 U.S.C. 119

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56(a) which occurred between the filing date of the prior application and the national of PCT international filing date of this application.

(Application Serial No.)	(Filing Date)	(Status)
60/188,325	09 MARCH 2000	

POWER OF ATTORNEY: *As a named Inventor, I hereby appoint the following attorney(s) and/or Agents(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith SCOTT MILLER, Reg. No. 32,278, SHARMINI N. GREEN, Reg. No. 41,410 and DENNIS S. MORRIS, Reg. No. 38,975*

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(Please Print)

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I further declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

SIGNATURE OF INVENTOR 1	SIGNATURE OF INVENTOR 2
DATE	DATE
SIGNATURE OF INVENTOR 3	SIGNATURE OF INVENTOR 4
DATE	DATE

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Return to: Kristin Freebairn

Client No. 1-317-001
Docket No. 6/081

THE U.S. PATENT AND TRADEMARK OFFICE MAIL ROOM HEREBY ACKNOWLEDGES RECEIPT OF THE FOLLOWING DOCUMENTS:

Receipt is hereby acknowledged of the following: Transmittal letter for Non-Provisional Patent Application w/Certificate of Mailing; specification, claims, abstract and formal drawing sheets); unexecuted Declaration and Power of Attorney; unexecuted Small Entity Status; check; and this post card

In Reference of: Oskar PAINTER, et al for the invention entitled "MICRO-CAVITY LASER" to be assigned to California Institute of Technology and Aleph Lightgate Corporation

Express Mail Label No. **EL631470561US**
Mailing Date: March 09, 2001